

NASA Advanced Exploration Systems: Advancements in Life Support Systems

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The NASA Advanced Exploration Systems (AES) Life Support Systems (LSS) project strives to develop reliable, energy-efficient, and low-mass spacecraft systems to provide environmental control and life support systems (ECLSS) critical to enabling long duration human missions beyond low Earth orbit (LEO). Highly reliable, closed-loop life support systems are among the capabilities required for the longer duration human space exploration missions assessed by NASA's Habitability Architecture Team.

Nomenclature

NASA	=	National Aeronautics and Space Administration
AES	=	Advanced Exploration Systems
LSS	=	Life Support Systems
ECLSS	=	environmental control and life support systems
LEO	=	low Earth orbit
ISS	=	international space station
EM	=	Environmental Monitoring
SMT	=	System Maturation Team
CO ₂	=	Carbon Dioxide
O ₂	=	Oxygen
CDRA	=	Carbon Dioxide Removal Assembly
CRCS	=	CO ₂ Removal and Compression System
CAMRAS	=	Carbon Dioxide and Moisture Removal Amino Swing Bed
EVA	=	Extra-Vehicular Activity
HEPA	=	High-Efficiency Particulate Air
CDS	=	Cascade Distillation System
RO	=	reverse osmosis
IWP	=	Ionomer-membrane Water Processor
SAM	=	Spacecraft Atmosphere Monitor
CSA-CP	=	Compound Specific Analyzer – Combustion Products
CPM	=	combustion products monitor
ppm	=	Parts per million

I. Introduction

The Advanced Exploration Systems (AES) Life Support Systems (LSS) project is focused on four areas: architecture and systems engineering for life support systems, environmental monitoring, air revitalization, and

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wastewater processing and water management. Starting with the international space station (ISS) life support systems as a point of departure (where applicable), the mission of the LSS project is three-fold:

1. Address discrete LSS technology gaps (see Table 1)
2. Improve the reliability of LSS systems
3. Advance LSS systems towards integrated testing on the ISS (see Figure 2)

This paper summarizes the work being done under the AES LSS project to meet these objectives. Details will be given on the following focus areas: Air Revitalization, Wastewater Processing & Water Management, Environmental Monitoring, and Systems Engineering & Architecture. Together these four areas represent the entire LSS architecture for human spaceflight as is depicted in Figure 1. Also provided are references to numerous other papers that go into greater technical detail on the technologies under development by the LSS project.

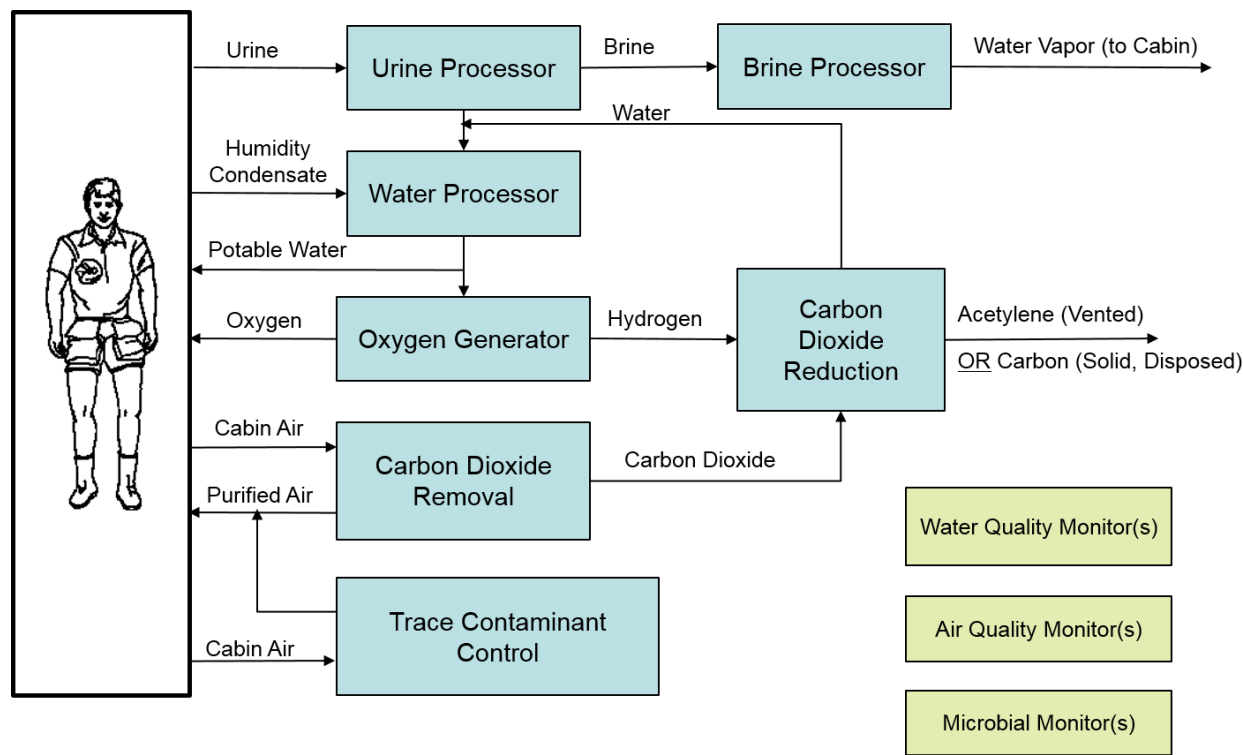


Figure 1: Simplified LSS Schematic

Over the past two years, the NASA Environmental Control and Life Support Systems (ECLSS) and Environmental Monitoring (EM) System Maturation Team (SMT) has identified the ECLSS-EM capability gaps for long duration human mission both in microgravity beyond low Earth orbit (LEO) and for partial gravity on a planetary surface. These gaps are summarized in Table 1. The SMT then developed roadmaps laying out the plan to close these critical gaps between now and ISS end of life – presently slated for 2024 [1]. ISS end of life was chosen as many gap closures culminate with a demonstration of the relevant technology (or technology improvement) on ISS. The LSS project is working on closures to many of the capability gaps listed, as will be detailed in the remainder of this paper.

Table 1: ECLSS and Environmental Monitoring System Maturation Team Identified Capability Gaps [2]

Function	Capability Gaps	Long Duration ug Hab	Planetary Surface
CO ₂ Removal	Bed and valve reliability; ppCO ₂ <4800 mg/m ³ (<2 mmHg)	X	X

Trace Contaminant Control	Replace obsolete sorbents w/ higher capacity; siloxane removal	X	X
Particulate Filtration	Surface dust pre-filter		X
Condensing Heat Exchanger	Durable, chemically-inert hydrophilic surfaces with antimicrobial properties	X	X
O ₂ recovery from CO ₂	Recover >75% O ₂ from CO ₂	X	X
O ₂ generation	Smaller, reduced complexity	X	X
High pressure O ₂	Replenish 3000 psi O ₂ for EVA; provide contingency medical O ₂	X	X
Water microbial control	Common silver biocide with on-orbit re-dosing	X	X
Wastewater processing	Increased water recovery from urine (>85%), reliability, reduced expendables, dormancy survival	X	X
Urine brine processing	Water recovery from urine brine >90%	X	X
Atmosphere monitoring	Smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), targeted gas (event) monitor	X	X
Water monitoring	In-flight identification & quantification of species in water	X	X
Microbial monitoring	Non-culture based in-flight monitor with species identification & quantification	X	X
Particulate monitoring	On-board measurement of particulate hazards	X	X

II. Air Revitalization

The air revitalization task under LSS is comprised of work in carbon dioxide removal, oxygen generation and recovery and trace contamination and particulate control. Current state of the art for these systems is CO₂ removal at ppCO₂ <4 mmHg [3], O₂ recovery at ~40% and both passive (filters) and active trace contamination and particulate control [4]. As was stated in Table 1, the capability gaps identified for air revitalization for human missions beyond LEO are:

- CO₂ Removal Bed and valve reliability; ppCO₂ <4800 mg/m³ (<2 mmHg)
- Replace obsolete trace contaminant control sorbents w/ higher capacity; siloxane removal
- Surface dust pre-filter
- Recover >75% O₂ from CO₂
- Smaller, reduced complexity O₂ Generation hardware
- Replenish 3000 psi O₂ for EVA; provide contingency medical O₂

The LSS project is doing work in many of these areas.

A. CO₂ Removal

Flight crew have reported that higher levels of CO₂ have an effect on their ability to perform tasks [5]. Reducing the ppCO₂ to less than 4800 mg/m³ (<2 mmHg) is therefore a high priority. The LSS project is investigating multiple technology paths to close this capability gap.

The Carbon Dioxide Removal Assembly (CDRA) on the ISS is a four bed molecular sieve technology using sorbents to remove CO₂. To address issues with the current system, LSS is testing other sorbents available in industry to quantify crush strength, water absorption, and hydro-thermal stability to determine if there are other

sorbents that will be less prone to dusting and can perform better in the known ISS environment conditions than the current sorbents in use. The LSS project is also investigating the geometry of the beds to determine if a circular cross section will be more efficient than the current rectangular cross section [3].

The LSS project is also developing a CO₂ Removal and Compression System (CRCS). CRCS is a two bed system that utilizes sorbents for removing CO₂. The CRCS design adds the capability to compress the CO₂ for storage for the CO₂ Reduction process [6]. Currently on the ISS an additional compressor is needed to compress the CO₂ delivered from the CDRA.

Solid and liquid thermal amines are also being investigated as an alternative to the current state of the art technology. Solid amine technology is used on the Carbon Dioxide and Moisture Removal Amino Swing Bed (CAMRAS) system on the ISS that was originally developed as a technology demonstration and is now being used to supplement the CDRA during high peak CO₂ times. The CAMRAS design loses water on orbit, so technologies to recover the water are being developed. The LSS project is also testing other solid amines to determine the best technology to use in this system.

Liquid amines offer the potential advantage of being low power, low mass, and high reliability systems, however, the challenge is understanding how the liquid will behave in a microgravity environment. A technology demonstration, Capillary Structures for Exploration Life Support, is being developed to understand the behavior of liquid amines. The technology demonstration is planned for a 2017 launch to the ISS. In parallel LSS is testing liquid amine formulations to determine the best liquid amine formula and system configuration.

At the end of fiscal year 2016 a gate review will be held to assess the status of the technologies being investigated to determine if the technology maturity warrants continued funding. A technology down select is planned at the end of fiscal year 2017 to decide which technology or technologies will be developed for a technology demonstration on the ISS. The CO₂ Removal technology demonstration is planned to launch in 2021.

B. O₂ Generation/Carbon Dioxide Reduction

Oxygen generation on the ISS is performed by using water electrolysis to separate the hydrogen and oxygen atoms. The oxygen is released to the cabin air, the hydrogen is vented overboard. This technology works very well to generate oxygen. To achieve the higher recovery rate the hydrogen can be used to reduce carbon dioxide removed from the cabin air, resulting in a higher oxygen recovery. Furthermore, technologies to pressurize oxygen to fill Extra-Vehicular Activity (EVA) tanks to 3000 psi on the spacecraft are being studied.

To increase the oxygen recovery rate to meet the stated goal of 'Recover >75% O₂ from CO₂', the LSS Project is investigating two technologies. The first technology is based on a Bosch reaction. This technology uses the stored CO₂ removed from the cabin air and combines it with the hydrogen by-product from oxygen generation. This process produces water which can be electrolyzed for additional oxygen. Solid carbon is a by-product of this process. One challenge for this process is determining what to do with the solid carbon by-product. The Bosch technology is potentially capable of recovering 100% of the oxygen from metabolic CO₂ [7].

The second technology uses a Sabatier reaction combined with methane post-processing. The Sabatier reaction combines CO₂ with the hydrogen from oxygen generation to produce water and methane. The methane is partially pyrolyzed in a plasma reactor to form hydrogen and acetylene. The hydrogen is sent back to the Sabatier to reduce more CO₂ and produce additional water, which can be electrolyzed to yield oxygen. The acetylene gas is vented overboard. The total oxygen recovery from metabolic CO₂ using the Sabatier reaction and methane post-processing is approximately 90% [8].

A down select of the CO₂ reduction technologies is planned for the end of fiscal year 2018. In 2019 the design for a technology demonstration of the down selected will start with the goal of launching the technology to the ISS at the end of fiscal year 2022.

To address the identified gap of 'Replenish 3000 psi O₂ for EVA; provide contingency medical O₂', the LSS project is investigating three technologies. One technology is to develop a replacement of the sub-system of the current ISS Oxygen Generation Assembly where the electrolysis of water occurs. The new design will have the capability to generate oxygen at ambient pressure and at high pressure. Two other technologies scavenge oxygen from the cabin air and then compresses the oxygen. One technology uses a pressure swing absorption system to scavenge oxygen. The other system utilizes a ceramic membrane to separate the oxygen from the cabin air. High pressure oxygen is needed for surface missions. On-going studies of exploration transit scenarios are trading the need to have a high pressure oxygen system or to carry tanks of pressurized oxygen. Therefore, a down select of these technologies has not been established.

C. Trace Contamination and Particulate Control.

Trace contamination control is necessary to remove contaminants from the ISS environment that may be harmful to the astronauts. The state of the art contamination control is performing as expected, however, the activated charcoal used in the system is no longer being produced. The ISS program has plenty of this material for the life of the ISS but a new material will be needed for missions beyond ISS. The LSS project is testing alternate materials to use in place of the obsolete activated charcoal. The LSS is also investigating new packing ideas for a trace contaminant system to develop a smaller unit that also is easy to maintain. Through the Small Business Innovative Research program an advanced Microlith[®] catalytic oxidizer has been developed and is being tested. Also being investigated is high flow/low aspect ratio and low flow/high aspect ratio designs. The current plan is to complete testing of materials and development hardware testing and finalize the design approach for a technology demonstration on the ISS in fiscal year 2022.

Particulate control is necessary to ensure astronauts do not inhale particulates in the cabin air. On the ISS High-Efficiency Particulate Air (HEPA) filters are used to filter particulates from the cabin air. The LSS project is working to understand the particulate environment on the ISS and investigating filter designs to reduce logistics and crew maintenance time [4]. To understand the particulate environment the LSS project has developed an experiment to collect particles at the ISS HEPA filters (see Section IV.C). The results of this experiment will inform the design for filtration system designs.

On the ISS the HEPA filters used for particulate filtration are replaced periodically, and between replacements the filters are cleaned with a vacuum cleaner. To reduce logistics and crew maintenance time, the LSS project is developing a filter that scrolls the filter media across the intake duct. This design allows for the filter media to automatically scroll to provide clean filter media without the need to vacuum. Additionally the packaging of the filter media reduces logistics as it allows for more equivalent filter media to be packaged in this design when compared to the current HEPA filters used on the ISS. A prototype of the filter is in chamber testing at Marshall Spaceflight Center. Mars surface dust is a concern with astronauts returning from surface EVAs and dust being brought into the surface habitat from the EVA suits. The LSS project is engaged in discussions addressing Mars surface dust to ensure filtration designs can filtrate or will be evolvable to filtrate Mars dust.

III. Wastewater Processing and Water Management

A major goal of the LSS project is the development of water recovery systems to support long duration human exploration beyond LEO. Current space station wastewater processing and water management systems distill urine and wastewater to recover water from urine and humidity condensate in the spacecraft at a ~90% recovery rate [9]. As was stated in Table 1, the capability gaps identified for wastewater processing and water management for human missions beyond LEO are:

- Development of a common silver biocide with on-orbit re-dosing
- Increased water recovery from urine (>85%), reliability, reduced expendables, dormancy survival
- Water recovery from urine brine >90% [enables 98% total water loop recovery]

The LSS project is working on all three of these gaps.

A. Silver Biocide

The current state of the art in biocides on the ISS utilizes both silver (Russian Segment) and iodine (U.S. Segment) based water disinfection systems. The iodine system requires removal of part or all of the iodine before consumption – because of this and the desire to only have one biocide for exploration missions, the LSS project is working on the development of a common silver biocide with on-orbit re-dosing capability. Current work is focused on the development of an electrolytically-generated silver ion dosing system. A study on the depletion rates of electrolytically-generated silver on common spacecraft wetted materials of construction has been completed. Based upon these findings, a conceptual design for a silver biocide dosing system was developed and built. That system is presently being tested.

Following completion of this testing, a flight-forward design will be completed, built and tested. In parallel, systems analysis is being performed to ensure the system being developed can be used across all platforms and to fully understand the system-, architectural-, and mission-level implications of moving to all silver-based disinfection systems. In order to support exploration milestones, including the potential need to test a silver biocide dosing system on station, early feasibility testing and analysis will continue under the LSS project through the 2020 timeframe.

B. Urine Processing

The current state of the art in urine processing on the ISS utilizes vapor compression distillation followed by multi-filtration and catalytic oxidation. This process produces potable water at an ~90% total recovery rate. For human exploration missions beyond LEO, the goal is ‘Increased water recovery from urine (>85%), [improved] reliability, reduced expendables, [and] dormancy survival’. To achieve this, the LSS project is doing work in several areas.

Over the past few years, the LSS project has done testing and development work on the Cascade Distillation System (CDS). CDS is urine processor that utilizes five stage vacuum rotary distillation [10]. The CDS technology has been developed through a collaboration between NASA and Honeywell International. Over the past few years, a CDS 2.0 design has been evolved – this design takes the current ground prototype and modifies it for micro-gravity operation on ISS. A system requirements review and preliminary design review have been completed. Through recent discussions with the International ECLSS SMT, it has been confirmed that the Russian Space Agency plans to fly a CDS variant to the ISS in the next year. This flight demo will serve as a validation of the CDS technology in micro-gravity so work by NASA on the CDS 2.0 system has been put on hold pending results of the Russian CDS flight demonstration and on-going performance of the existing ISS urine processor.

The LSS project is also doing development work on the use of reverse osmosis (RO) membranes in the water processor assembly. The goal of this task is to reduce the expendables associated with the multi-filtration beds in this system. Presently the beds need to be changed out every few months - this is a significant driver of consumable mass. The RO membrane work shows promise for cutting this consumable mass in half or better. Early design and prototyping has been completed for the RO membrane system [11]. Testing is on-going and will complete in early 2017. Once feasibility is demonstrated, the design for incorporating this system into the existing water processor will be completed. A flight demonstration is targeted for 2021.

C. Brine Processing

Recovery of potable water from wastewater is essential to the success of long-duration human spaceflight. For human missions to Mars, the technology maturation (TA 207) objective is to recover >98% of the water from wastewater sources (urine, humidity condensate, etc.). To reach these goals and satisfy the capability gap of ‘water recovery from urine brine >90%’, the development of a brine processor is required. Building upon the work done under NASAs Small Business Innovation Research program, the LSS project is working with Paragon, Inc. to develop the Ionomer-membrane Water Processor (IWP) brine processor for flight demonstration on the ISS.

The IWP utilizes forced convection of dry, heated, spacecraft cabin air coupled with membrane distillation to purify and recover water from urine brine [12]. The water vapor generated is released from the IWP into the cabin environment where it is collected and condensed by the existing spacecraft condensing heat exchanger(s). This water is then further processed by the existing Water Processor Assembly to potable standards. To meet the >90% water recovery from urine goal stated above, the IWP is required to recover at least 40% of the water from the urine brine. A requirements review for the brine processor was recently held along with a phase 0 ISS safety review. The next milestone will be the system design review, followed by the phase 1 ISS safety review. Critical design review for the brine processor flight demonstration is slated to occur spring 2017, with flight demonstration to occur in late 2018.

IV. Environmental Monitoring

In an enclosed spacecraft that is constantly operating complex machinery for its own basic functionality as well as science experiments and technology demonstrations, it’s possible for the environment to become compromised. While current environmental monitors aboard the ISS will alert crew members and mission control if there is an emergency, long-duration environmental monitoring cannot be done in-orbit as current methodologies rely partially on taking grab samples and sending these environmental samples back to Earth. As was stated in Table 1, the capability gaps identified for environmental monitoring for human missions beyond LEO are:

- Smaller, more reliable major constituent analyzer, in-flight trace gas monitor (no ground samples), targeted gas (event) monitor
- In-flight identification & quantification of species in water

- Non-culture based in-flight monitor with species identification & quantification
- On-board measurement of particulate hazards

The LSS project is doing work in many of these areas.

A. Major Constituent Analyzer/Trace Gas Monitor

The current state of the art in air monitoring is the major constituent analyzer and the air quality monitor. Together these monitors are heavy and bulky. For exploration missions, the goal is to develop ‘smaller, more reliable’ monitors with in-flight analysis capability. The LSS project is working on the Spacecraft Atmosphere Monitor (SAM), a miniature gas chromatograph/mass spectrometer (GC/MS) system capable of real time measurement of major constituents and trace volatile organic compounds in the cabin atmosphere. The development of a miniature GC/MS for use in SAM allows for a small size (22.2 cm x 24.1 cm x 19.1 cm), low mass (9.5 kg, including consumables), and low power (34 watts) monitor. The SAM is designed to provide data via Ethernet or wireless [13].

The SAM is planned to fly as a technology demonstration on the ISS in fiscal year 2018. SAM is planned to be mounted in an Expediting the Process of Experiments to the Space Station Rack in a single locker volume. The SAM can be removed from the locker and located anywhere in the ISS to take location specific measurements. The SAM has completed the Systems Requirements Review and Systems Design Review and the Phase 0/I and Phase II safety reviews. A qualification unit is being developed for testing. Two flights units are planned to be built.

B. Targeted Event Monitor

For spacecraft anomalies, it is of critical importance to be able to perform targeted monitoring of certain constituents – such as combustion products, ammonia, etc. The current state of the art for combustion products is the Compound Specific Analyzer – Combustion Products (CSA-CP). The CSA-CP measure measures: % O₂, ppm CO, ppm HCl and ppm HCN but requires annual calibration and is experiencing issues with parts obsolescence.

The LSS project is currently working on the combustion products monitor (CPM). The CPM is a portable laser-based monitor for CO, O₂, CO₂, H₂O, HCN, HCL and HF concentrations in real-time. The CPM will require no calibration or consumables for an exploration (3 year) mission. A prototype CPM is presently being built for testing in the fall of 2016. If selected for further development, the CPM could be ready for ISS demonstration in late 2018.

C. Measurement of Particulate Hazards

On the ISS, smoke does not rise to the ceiling and crumbs do not fall to the floor, which demonstrates the unique characteristics of aerosol behavior in low gravity. Dust and particle-laden air has been a recurring complaint of the crew as they have experienced nose and eye irritation as well as allergies. This is an indication of high concentrations of inhalable particles, defined as ≤ 100 micrometer in diameter. To quantify the particulate load in the air on ISS and satisfy the ‘On-board measurement of particulate hazards’ gap previously identified, the LSS project has developed an Aerosol Sampler flight experiment to provide data on quantity and sizes of particles in ISS ambient air. Particles will be collected with a battery-powered Active Sampler which is a modified of the shelf thermophoretic sampler and customized Passive Samplers, all manufactured by RJ Lee Group (of Monroeville, PA). The two types of samplers are not monitors or sensors, only collectors, and samples will be returned to Earth for analysis by powerful transmission electron microscopes. The flight experiment has completed design, build and certification and is slated to launch in summer/fall 2016. Results will be obtained 6 months to 1 year after launch and will both inform the design of future particulate monitors for spacecraft and to validate and refine the ISS particulate database.

V. Systems Engineering & Architecture

With so many complex systems comprising life support in space, it is important to understand the overall system requirements to define life support system architectures for different space mission classes, ensure that all the components integrate well together and verify that testing is as representative of destination environments as possible. The LSS project's main focus for systems engineering and architecture is to define the reference LSS architecture for exploration missions [14], identify applicable requirements and standards [15], manage interfaces and integration [16], assist in evaluations/down selects of competing technologies and provide direction for testing of technologies.

VI. Conclusion

As human seek to venture beyond LEO, the criticality of having a reliable life support system increases. The LSS project under NASA's AES Programs is actively working on addressing community identified LSS capability gaps in preparation for said missions. Starting with ISS systems as a point of departure, where applicable, the project is evolving these systems and developing new systems to be smaller, lighter and more reliable and to further close the water and air loops to reduce the consumable mass needed. As part of this effort, a series of LSS technology demonstrations on the ISS are planned between now and ISS end of life – these demos are summarized in Figure 2.

Figure 2: LSS Planned Flight Demonstrations

	FY17	FY18	FY19	FY20	FY21	FY22	Flight Demo Goal
Spacecraft Atmosphere Monitor (S.A.M.)			▲				Continuous measurement of major constituents, on-demand measurement of trace VOCs.
Brine Processor Assembly (BPA)			▲				One year demonstration of >40% water recovery from urine brine.
Plasma Pyrolysis Assembly (PPA)				▲			Understand plasma performance in microgravity using Argon to form the plasma.
Aerosol Sampler	▲		▲				Obtain quantitative data on airborne particles in multiple ISS locations.
CO2 Removal						▲	Lower ppCO2 to 2mm Hg or less
CO2 Reduction						▲	>75% reduction of CO2 via Bosch or PPA or other technology.
Wastewater Processing					▲		RO Membrane Technology to reduce logistics replacement of Multifiltration Beds

Shaded Bar = Flight Demo Design/Build

▲ = Flight Demo Launch

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